Advanced Design Concepts for a SeaWinds Scatterometer Follow-On Mission[1]

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Abstract— The SeaWinds wind scatterometer was first launched in June of 1999, and has contributed significantly to the study of global climate phenomena and to the fidelity of operational weather forecasting. A second SeaWinds instrument is planned to be launched aboard the Japanese ADEOS-II platform in late 2001, and operate until mid-decade. To extend the important Ku-Band scatterometer data base to the end of the decade and beyond, a follow-on system to the SeaWinds series of scatterometers is being developed. The goals for this system are to continue the core Ku-Band backscatter measurement, to further improve spacecraft accommodation constraints so as to be easily operated on a variety of platforms, and -- where possible under existing cost constraints -- improve wind retrieval performance. It is shown that a system, which meets these objectives, can be achieved by the addition of polarimetric measurement capability to the existing SeaWinds approach. Polarimetric scatterometry is demonstrated to improve wind performance without impacting instrument complexity or cost, and has the long term potential to further ease spacecraft accommodation requirements.

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1. INTRODUCTION

The SeaWinds wind scatterometer is a Ku-Band radar developed to measure surface wind speed and direction over the global oceans [4]. The first launch of the SeaWinds instrument occurred aboard the QuikSCAT spacecraft in June, 1999. Although other wind scatterometers have flown in the last two decades – including the C-Band ERS-1,2 series of instruments and the Ku-Band NASA Scatterometer (NSCAT) – these systems employed multiple long "fan-beam" antennas [1], [3]. SeaWinds is the first scatterometer system to use the scanning "pencil-beam" antenna approach. Unlike fan-beam systems which often require complex deployments and large fields-of-view, pencil-beam systems employ a single conically scanning antenna. The single dish antenna design is generally easier to accommodate on spacecraft. This feature was demonstrated when the QuikSCAT mission was developed to quickly replace the loss of the NSCAT data [2]. Within a period of one year, a commercial spacecraft bus was procured and an existing SeaWinds instrument was easily integrated with few modifications to the bus architecture and no instrument deployments. Another key advantage of the pencil-beam scatterometer approach is that measurements from each beam are made at a constant incidence angle. This simplifies model function estimation, and also greatly simplifies the use of backscatter values for land and cryosphere applications.

Having operated flawlessly in orbit for over a year, the QuikSCAT mission has validated the conically-scanned pencil-beam scatterometer concept. SeaWinds/QuikSCAT derived ocean winds have contributed significantly to the scientific study of air/sea interactions, and are also being increasingly used to improve the fidelity of numerical weather forecasts. The launch of the SeaWinds instrument on the ADEOS-II spacecraft in late 2001 will extend the Ku-Band scatterometer data base into the middle of the decade.

Due to the successful use of SeaWinds data in a variety of Earth science disciplines, plans are underway to develop a follow-on scatterometer system to begin operation around 2005 [6]. In this paper, the advanced design concepts proposed for the SeaWinds follow-on mission are presented. Here design features which can improve the scatterometer measurement performance, as well as the required programmatic constraints of spacecraft accommodation are discussed. An innovative scatterometer technique, which employs polarimetric backscatter measurements, is identified as a low-cost enhancement, which will significantly improve wind retrieval performance. It is also discussed how the polarimetric technique may be employed

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to further reduce the field-of-view requirements for pencil-beam scatterometers, and consequently further ease spacecraft accommodation issues.

2. Advanced Scatterometer Issues

The overriding consideration for a follow-on scatterometer mission is the continuity of the Ku-Band backscatter and wind data base. Preferably, the follow-on measurements are to be obtained at the same incidence angles as SeaWinds. The continuation of measurements collected under the same conditions will facilitate the detection of subtle, multi-decade climate change signatures such as those induced by El Nino or long-term global warming.

A second major consideration is that the follow-on instrument must be low cost and be easily accommodated aboard a variety of different spacecraft platforms. This will enhance the ability of the instrument to be flown on "spacecraft of opportunity" (as was the case with QuikSCAT for example) as well as future operational systems. Consistent with this, the instrument mass and power should be the same as SeaWinds, or, preferably, smaller. Current technology trends should make this latter requirement a relatively straightforward one to satisfy. Also critical is the accommodation and associated field-of-view of the rotating antenna. The current SeaWinds system is mounted on the nadir-facing side of the spacecraft and requires a 360 field-of-view as it rotates. If possible, it is desirable to reduce this so that the scatterometer may be mounted on the top-side of the spacecraft allowing abundant room for other nadir facing sensors.

Clearly, a desire for any follow-on mission is that of improved sensor measurement performance. For weather forecasting applications, it is critical that measurement revisit time be as short as possible. With the current SeaWinds instrument, the 1800 km measurement swath provides near-global coverage every 24 hours. Because the quality of the scatterometer data varies over the swath, some performance degradation occurs near the spacecraft sub-track region and at the extreme outer edges of the swath. Some researchers have found it necessary to only include the data from the "sweet spot" of the swath which excludes these regions. It is therefore highly desirable to improve wind performance in the sub-track and outer-swath regions so that the full benefit of the wide pencil-beam swath may be realized.

3. The Polarimetric Scatterometer Technique

An innovative technique that meets the requirements of the previous section is to add polarimetric measurement capability to the current SeaWinds instrument architecture. Polarimetric scatterometry can be added to the SeaWinds design with minimal cost impact while continuing to produce measurements identical to the current SeaWinds instrument. Additionally, polarimetric scatterometry can be used to either ease accommodation on spacecraft or to improve wind performance. Before we develop and describe this approach, however, we will first briefly review the standard SeaWinds wind retrieval approach.

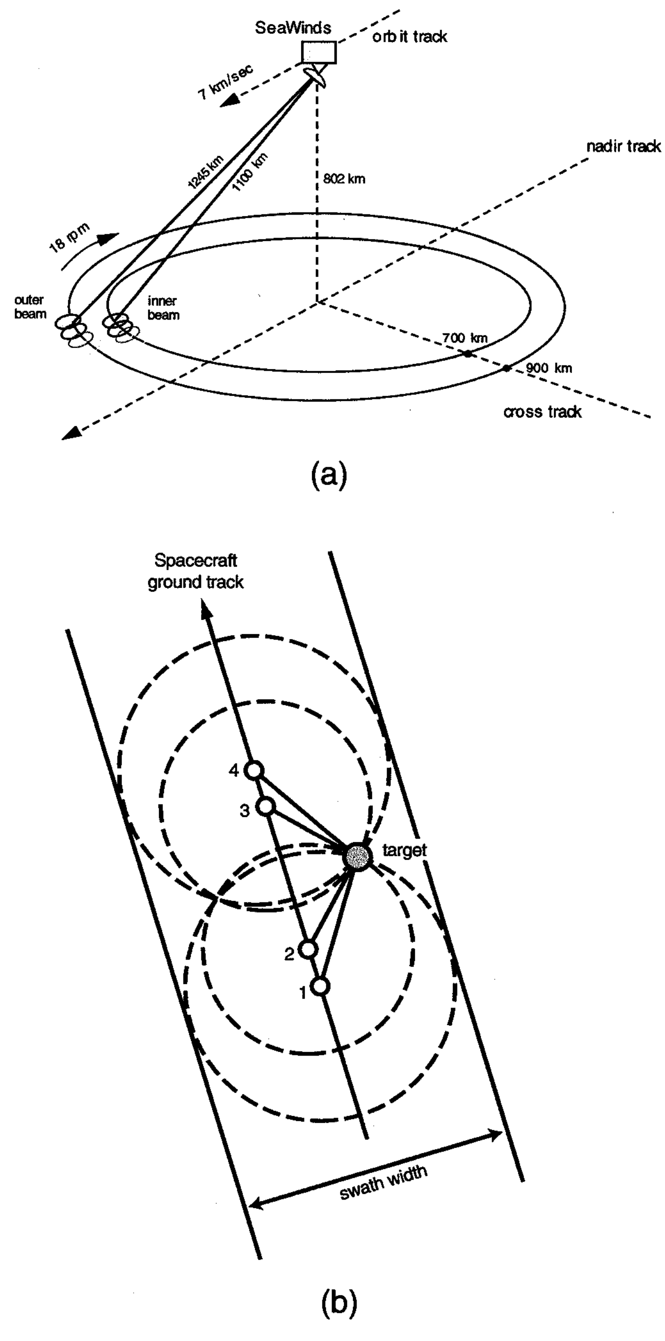

Figure 1: SeaWinds measurement geometry.

Conventional Wind Scatterometry

In conventional wind scatterometry, the normalized radar backscatter cross-section, σ_0, of given point on the ocean surface is viewed from multiple azimuth angles [3]. This is accomplished with the SeaWinds systems as shown in Fig.

1. As the satellite passes, the surface is viewed four times: twice by the inner beam looking first forward then aft, and twice by the outer beam in the same fashion. The four measurements are inverted using the geophysical model function (GMF) to solve for the wind speed and direction. To aid in the wind retrieval, the SeaWinds inner beam is H-polarized and the SeaWinds outer beam is V-polarized.

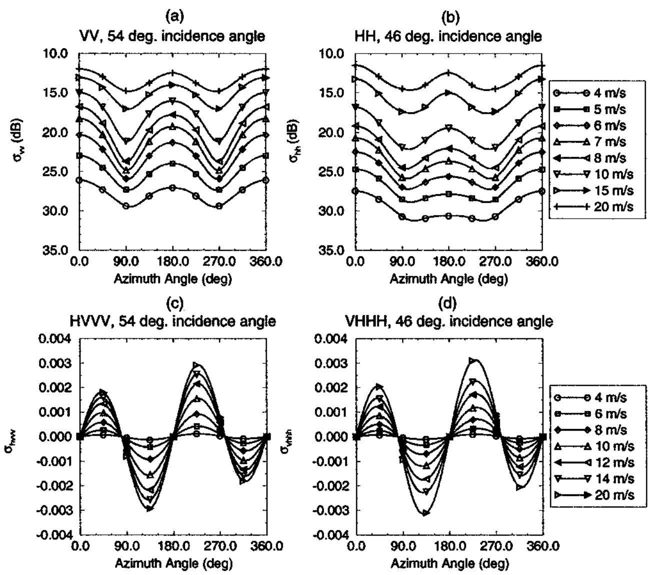

Figure 2: Geophysical model functions for the conventional co-polarized return -- (a) and (b) -- and the polarimetric correlation term -- (c) and (d).

With scatterometer systems to date, only the *co-polarized* component of the backscatter is measured. For example, in the case of the SeaWinds outer beam, a V-polarized signal is transmitted and only the power in the V-polarized return is detected in order to calculate σ_0. The co-polarized GMF is an even function of illumination azimuth angle as shown in Fig. 2 a and b. When inverted in the presence of noise, the wind estimation procedure does not yield a unique wind estimate but a set of wind ambiguities, as shown in Fig. 4 a and b. Often invoking the aid of global circulation models, the ambiguous wind can be resolved yielding the correct wind vector. This process, however, is error prone in the regions of the SeaWinds swath immediately adjacent to the satellite nadir track and in the outer edges of the swath where only the outer beam measurements are available.

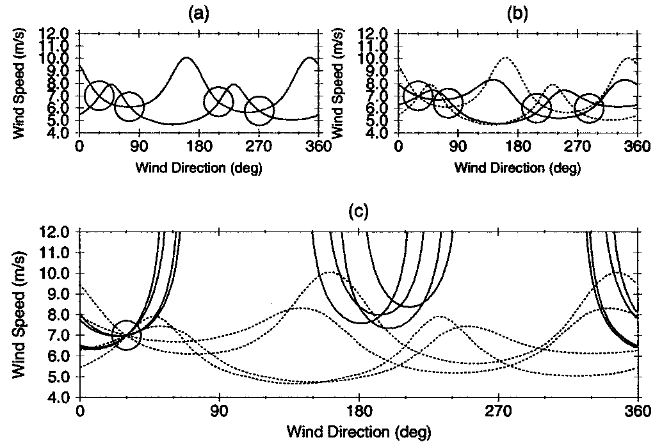

Figure 3: Wind vector solution curves for two co-polarized measurements (a), four co-polarized measurements (b), and with four polarimetric measurements (c).

Polarimetric Measurements

Theoretical and experimental studies have indicated that additional information may be provided to the wind retrieval by collecting *polarimetric* measurements of the sea surface backscatter [7]. With polarimetric measurements, one polarization -- V, for example -- is transmitted and both the co-polarized V backscatter and the cross-polarized H backscatter are measured simultaneously. The correlation between these backscattered energies is measured to calculate the polarimetric backscatter correlation coefficient σ_{hvvv} given by $\sigma_{hvvv} = \langle E_V E_H \rangle$ where Ev is the V-polarized backscatter signal and E_H is the H-polarized backscatter signal when a V-polarized transmit signal is used., and the brackets represent the time average. In general this polarimetric correlation term is a complex quantity. In a similar manner, an H-polarized transmit signal can be used to measure σ_{vhhh}. It is important to note that the polarimetric defined above is not the same as the cross-polarized return power which is given by $\sigma_{hvhv} = \langle E_H E_H \rangle$, when a V-polarized transmit signal is used and by $\sigma_{vhvh} = \langle E_V E_V \rangle$ when an H-polarized transmit signal is used.

Utilizing directional rough surface scattering theory, it can be shown that the terms σ_{hvvv} and σ_{vhhh} are an *odd* function of illumination azimuth, which is an orthogonal symmetry compared to the standard co-polarized measurements. When added to the wind retrieval process, this additional polarimetric information has the potential to reduce the number of ambiguities, as shown in Fig. 3c. It is this feature that makes the polarimetric capability desirable for implementation on follow-on missions.

4. Baseline Polarimetric System Design and Performance

A polarimetric scatterometer can be easily constructed by adding cross-polarization measurement capability to an existing pencil-beam scatterometer design such as SeaWinds [7]. A brief description of the current SeaWinds instrument is provided here for ease of reference.

As discussed in previous papers, the SeaWinds architecture employs a one meter diameter dish antenna with center feeds slightly scanned to generate two pencil-beams [4], [5]. The transmitter alternatively pulses the inner beam then the outer beam yielding an effective PRF for each beam of 92 Hz. This sampling rate, coupled with the antenna rotation rate of 18 rpm, produces measurements on the surface at 15 to 20 km spacing.

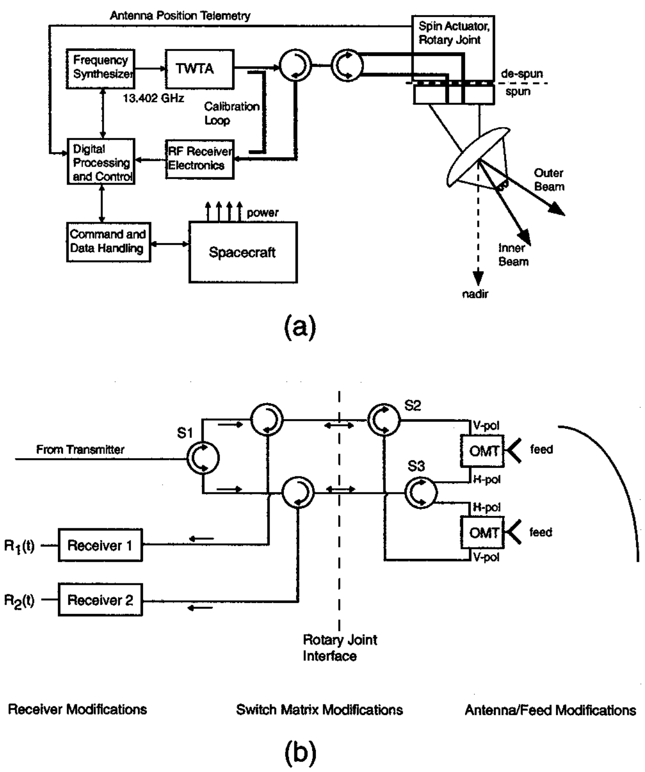

Figure 4: Baseline SeaWinds design (a) and polarimetric modification (b).

Figure 4 (a) depicts the basic design of the SeaWinds radar electronics. Upon command from the timing controller, the transmitter, which consists of a modulated signal generator driving a traveling wave tube amplifier (TWTA), issues a 1.5 ms duration, 110 Watt Ku-band pulse. The pulse is routed to either the inner or the outer beam and through a coaxial rotary joint to the spinning section of the antenna assembly. The echo return is likewise directed to the receiver where it is amplified, downconverted, and detected. Due to the motion of the satellite relative to the Earth, a Doppler shift of between +/- 500 kHz is imparted to the echo return signal as the antenna scans. To compensate for this effect and insure that the echo return is centered in the receiver bandwidth, a carrier offset frequency is computed as a function of the antenna azimuth and imparted to the transmit pulse. An important feature of any scatterometer system is the accurate calibration of the transmit power and receiver gain. In the SeaWinds instrument design, these parameters are measured simultaneously by periodically injecting the transmit pulse, attenuated by a known amount, into the receiver. A summary list of the key radar parameters is given in [4].

Polarimetric Modifications

Because SeaWinds has proven to be easily accommodated on spacecraft, we constrain our polarimetric design to be a simple modification to this existing system.

The necessary modifications to the SeaWinds design to add polarimetric capability are summarized in Fig. 4(b). In the antenna assembly, the feed system must be modified in order to allow the simultaneous reception of the two polarizations. This is done by employing dual-polarized feeds and orthomode transducers to separate the V and H components. The antenna design must also be modified to produce a very low cross-polarized component in order to minimize cross talk between the channels. Preliminary design studies have demonstrated that cross-polarization isolation levels of better than 35 dB can be achieved with an offset-fed antenna/feed configuration.

To handle the more complicated switching required for the polarimetric measurements, additional circulators and/or ferrite switches are necessary on both sides of the antenna rotary joint. The switching configuration shown in Fig. 4(b) is one (but by no means the only) strategy for routing the signals to insure that the co-polarized and cross-polarized returns are received simultaneously on each beam in turn. One advantage of the approach shown is that the RF connect across the rotary joint only requires two channels, just as in the current SeaWinds design.

The final modification is the addition of another receiver chain in order to obtain the polarimetric correlation measurements. As shown in Fig. 4(b), the conventional co-polarized measurements (the V and H polarized σ_0's respectively) are obtained by detecting the total signal power out of one of the receivers by forming $<R_1R_1^*>$ or $<R_2R_2^*>$ where R_i is the downconverted return signal in the *i*th channel. The polarimetric correlation components are derived from a measurement of $<R_1R_2^*>$. It is important to note that all the required modifications to implement polarimetric capability involve the use of fully mature technologies, and thus do not significantly increase the cost of the system.

Simulation Results

To evaluate the performance improvements associated with the polarimetric modifications, the JPL scatterometer end-to-end simulator was used. The results of the simulation study are shown in Fig. 5. In Fig. 5a, the wind direction errors for the nominal SeaWinds case (dotted line) and the polarimetric case (solid line) are shown as a function of cross-track distance for four different wind speed ranges. Similarly, in Fig. 5b., the wind speed retrieval errors are shown. Note that the addition of the polarimetric capability significantly improves wind retrieval performance, particularly in the swath regions near nadir and at the extreme edges of the swath. It is also important to point out that whereas the nominal SeaWinds simulation case was performed with the aid of numerical model "nudging," the polarimetric case was not. This means that the polarimetric system has the added benefit of providing wind measurements that are completely independent of any other data sources.

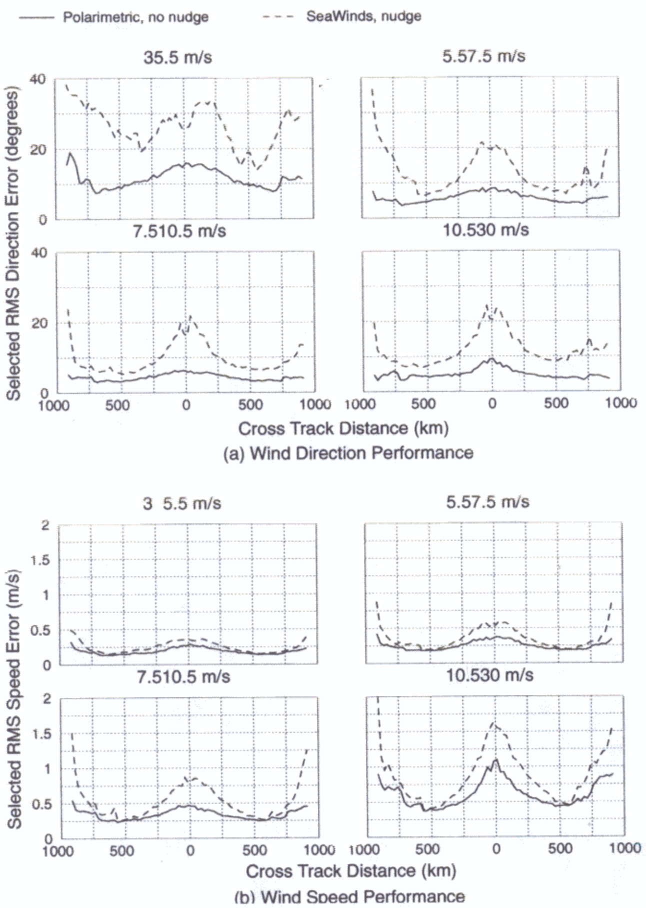

Figure 5: Simulated conventional vs. polarimetric performance results for wind direction error (a), and wind speed error (b).

It is traditional to refer to the swath region over which the scatterometer achieves the best performance as the "sweet spot." From Fig. 6, we define the sweet spot for the nominal SeaWinds case as being from about a cross-track distance of 150 km to 750 km on either side of the sub-satellite point, thus effectively excluding the regions near nadir and at the outer edge of the swath. The 24-hour Earth coverage for the SeaWinds sweet spot region is shown in Fig. 6.

If we conclude from Fig. 5 that the polarimetric capability effectively extends the sweet spot to be the entire swath, then the resulting 24-hour Earth coverage is given by Fig. 7. Note that the addition of polarimetric capability to the SeaWinds scatterometer system effectively extends the Earth coverage over which the best wind performance can be obtained.

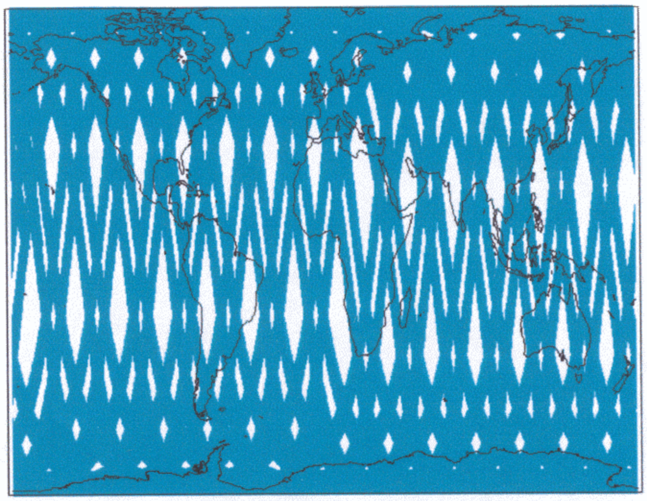

Figure 6: 24 hour coverage for sweet spot only.

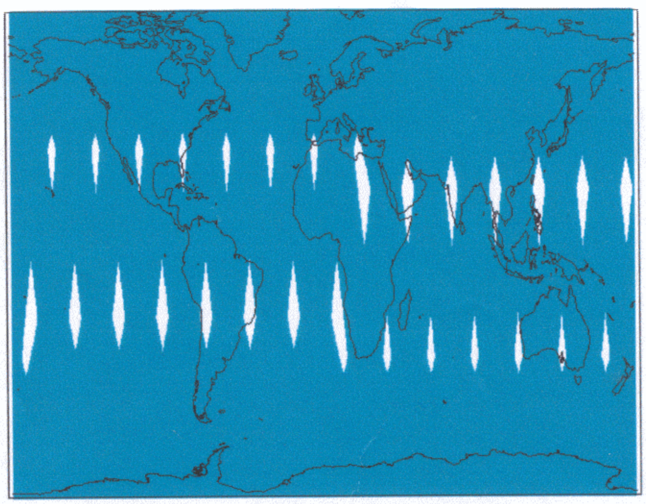

Figure 7: 24 hour coverage for full SeaWinds swath.

5. Polarimetric System with 180 Degree Field-of-View

In the previous section, an example was given of how the SeaWinds system can be easily improved by the addition of polarimetric capability. In this case, the fundamental SeaWinds antenna architecture and accommodation constraints are the same. Although the SeaWinds system has proven easy to accommodate on a variety of spacecraft, the system would be even easier to accommodate if the requirement for a wide 360 degree field-of-view for the scanning antenna was somehow reduced. Unfortunately, with a conventional co-polarized scatterometer system this is unachievable because a minimum of three azimuth looks at the surface are required for acceptable for wind vector retrieval.

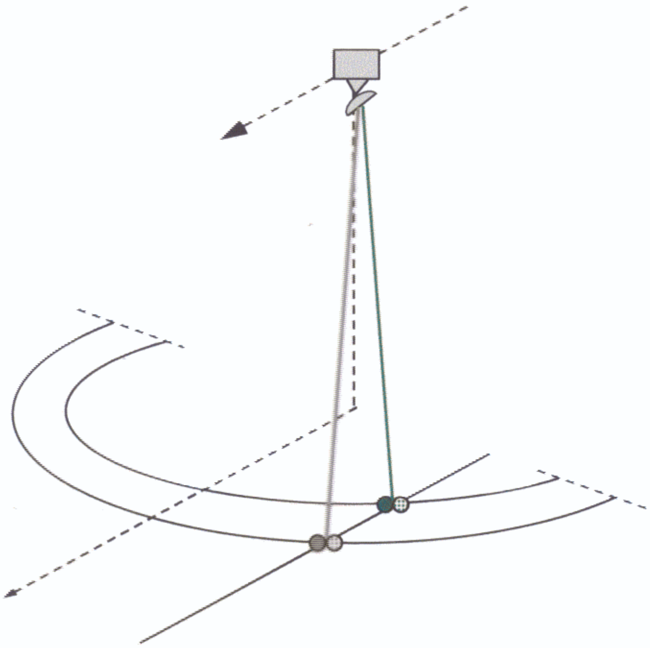

Figure 8: Polarimetric system with 180 degree scan.

Because the polarimetric model function has orthogonal symmetry to that the conventional model function, however, the addition of polarimetric measurements effectively adds an additional azimuth look to every co-polarized measurement obtained. Thus a polarimetric system which only scans 180 degrees, as shown in Fig. 8, has the potential to yield performance similar to the conventional system scanning 360 degrees. The performance of this system, however, is still not as good as the polarimetric systems which scans the full 360 degrees. Thus this system approach is not recommended by the immediate SeaWinds follow-on, but, following the successful demonstration of a polarimetric scatterometer, could be considered for future systems where instrument accommodation is extremely limited.

6. Conclusions

The SeaWinds instrument has proven to be a valuable tool in weather prediction and in the study of the Earth's climate. There is a strong desire to continue the Ku-Band wind data base throughout the decade by developing follow-on missions. A key innovation, which improves the scatterometer measurements while maintaining core features -- such as the same measurement geometry and ease of spacecraft accommodation – is polarimetric scatterometry. The addition of the polarimetric function to the basic SeaWinds design is shown to be straightforward and results in a significant improvement to instrument performance. In addition, polarimetric scatterometry has the potential to further ease the spacecraft accommodation issues associated with future pencil-beam scatterometers.

Acknowledgments

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